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Linear Optics Approach to Quantum Computing

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12 a. DISTRIBUTION / AVAILABILITY STATEMENT

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12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This is the final report for a three-year grant to investigate a linear optics approach to quantum computing. The main results of the study include a demonstration of a CNOT logic gate, a source of single photons on demand, a quantum memory device for photonic qubits, a small-scale circuit for photonic qubits, and a quantum error correction. The elimination of failure events using the quantum Zeno effect was proposed and is being investigated in a follow-on grant.

14. SUBJECT TERMS

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SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,

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REPORT OF INVENTIONS AND SUBCONTRACTS

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5. "SUBJECT INVENTIONS" REQUIRED TO BE REPORTED BY CONTRACTOR/SUBCONTRACTOR *(If "None," so state)*

NAME(S) OF INVENTOR(S) *(Last, First, Middle Initial)* a.	TITLE OF INVENTION(S) b.	DISCLOSURE NUMBER, PATENT APPLICATION SERIAL NUMBER OR PATENT NUMBER c.	ELECTION TO FILE PATENT APPLICATIONS *(X)* d. (1) UNITED STATES (a) YES	(1) UNITED STATES (b) NO	(2) FOREIGN (a) YES	(2) FOREIGN (b) NO	CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER *(X)* e. (a) YES	e. (b) NO
Franson, James D.	Optical Method for Quantum Computing	patent 6,678,450	✗		✗		✗	
Pittman, T.B., Franson, J.D., and Jacobs, B.C	Techniques for Performing Logic Operations ...	patent 6,741,374	✗					
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a. NAME OF AUTHORIZED CONTRACTOR/SUBCONTRACTOR OFFICIAL *(Last, First, Middle Initial)*	b. TITLE	c. SIGNATURE	d. DATE SIGNED
Franson, James D.	Principal Investigator	see original	10/30/05

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Additional patent applications:

Franson, J.D., Donegan, M.M., Fitch, M.J., Jacobs, B.C., and Pittman, T.B.
"Techniques for High Fidelity Quantum Computing",
patent application # 1911-1485

Pittman, T.B. Franson, J.D., and Jacobs, B.C.
"Techniques for Storing a Polarization State of a Single Photon for Retrieving on Demand During Quantum Computation"
patent application # 1905/1906-1485

Franson, JD., Jacobs, B.C., and Pittman, T.B.
"Techniques for Quantum Processing with Photons and the Zeno Effect"
Patent Application # 2018-0069

Franson, J.D., Jacobs, B.C., and Pittman, T.B.
"Nanocavities for Use in Quantum Information Processing"
Provisional application (number not available at this time)

FINAL PROGRESS REPORT

Foreword

This grant (DAAD19-02-1-0069) was for an investigation of a linear optics approach to quantum computing. At the time of the proposal, it had been suggested by Knill, Laflamme, and Milburn that quantum logic operations could be performed using linear optical elements, but their theoretical proposal did not appear to be feasible from an experimental point of view. As part of this proposal, we showed how quantum logic devices of this kind could be implemented in a practical way using polarization encoding. We went on to demonstrate many aspects of a linear optics approach to quantum computing, including quantum logic gates, a prototype quantum memory, a source of single photons on demand, small-scale quantum circuits, and quantum error correction. More recently, we showed how the probabilistic nature of these logic gates could be avoided by using the quantum Zeno effect to suppress the inherent failure events in an approach of this kind. As a result of this work, a hybrid optical approach of this kind appears to be one of the leading methods for a scalable approach to quantum computing.

This grant was subsequently combined with an augmentation grant (DAAD19-03-0097) to increase the scope of the work. Both grants are for the same research topic and a similar report will be submitted for both, as suggested by the sponsor in previous years.

It should also be noted that this work is being continued as part of a follow-on grant for a consortium involving the Applied Physics Laboratory, the University of Illinois, the University of Queensland, and other international groups. Although this is a final report, it does not signify the end of this important area of research.

Statement of the problem

The ability to implement quantum logic gates using linear optical elements, additional photons known as ancilla, and measurements made on the ancilla is illustrated in Fig. 1. Here the two logical qubits are combined with the ancilla using a network of linear optical elements. Measurements made on the ancilla after the leave the device are used to determine the need for feed-forward correction on the output qubits. The operation is probabilistic in the sense that certain measurement outcomes indicate that the output qubits contain an uncorrectable error.

Although logic operations of this kind are very stable and relatively simple, there are a number of problems that must be addressed: What is the best way to perform logic operations with the smallest error rate? How can single photons be generated for use in these devices. Is it possible to develop quantum memories for photonic qubits. Can these techniques be used to build more complex circuits? Can quantum error correction be performed using linear optics techniques? Answers to most of these issues were found during the course of this work.

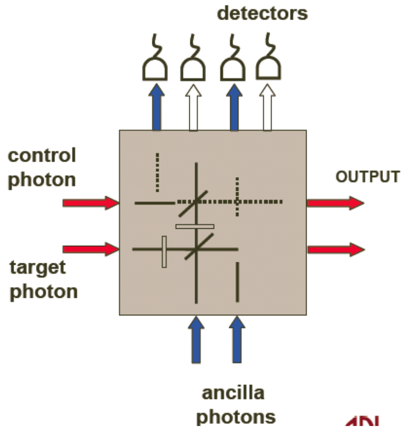

Fig. 1. Basic approach used in linear optics quantum computing.

Summary of the most important results

During the course of this work, we demonstrated a number of quantum logic operations, including a parity check, controlled CNOT gate, and full CNOT gate. Our CNOT gate is illustrated in Fig. 2. It consists of two polarizing beam splitters, two sets of detectors, and a pair of entangled ancilla photons. When one and only one photon is detected in each detector, we know that the correct logical output has been produced. This occurs ¼ of the time.

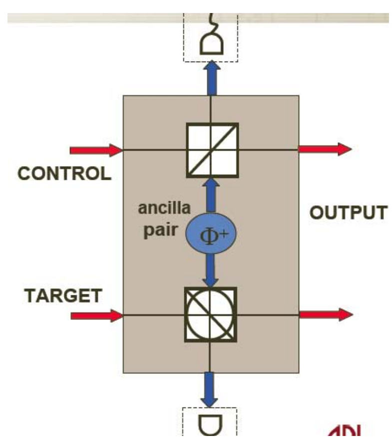

Fig. 2. The APL CNOT logic gate.

In order to demonstrate logic operations of this kind, it was necessary to develop a source of three indistinguishable photons. A photograph of the source and the first experimental demonstration of a CNOT logic gate for photonic qubits are show in Fig. 3.

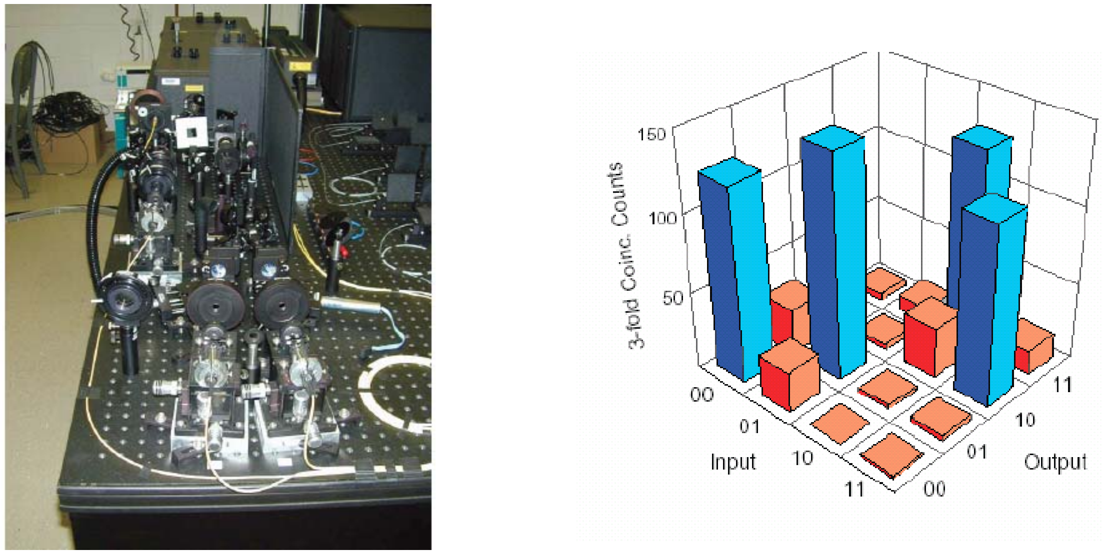

Fig. 3. Source of entangled photons and the first experimental demonstration of a CNOT gate for photonic qubits.

Another important logic device is a quantum encoder, which "copies" the value of a single input qubit into two output qubits. Our implementation of a quantum encoder and the corresponding experimental results are shown in Fig. 4.

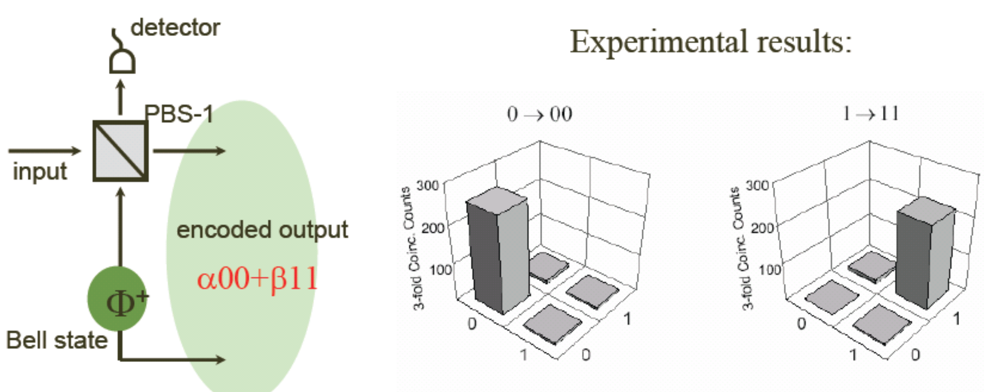

Fig. 4. Implementation of a quantum encoder and the corresponding expermental results.

One of the most important advantages of an optical approach to quantum computing is the fact that optical fibers or wave guides can be used to connect arbitrary quantum logic elements in analogy with the wires of a conventional computer. This capability is not a feature of most other approaches, such as ion traps. Fig. 5 shows our demonstration of the first quantum circuit using photonic qubits, which shows that logic devices can, indeed, be connected in this way. This circuit utilizes two XOR logic gates to calculate the parity of three arbitrary input qubits.

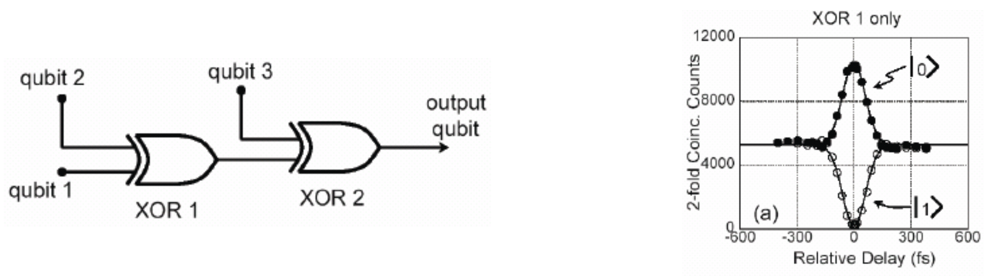

Fig. 5. First demonstration of a small-scale quantum circuit using linear optical elements and connections based on optical fibers.

Another important requirement for the development of a quantum computer is the ability to perform quantum error correction. In a linear optics approach, by far the most common error source is the accidental measurement of the value of a qubit. This type of error can be corrected using the encoding illustrated in Fig. 6 along with our implementation of it. The experimental results from this experiment are illustrated in Fig. 7.

$$|0\rangle \rightarrow |0_L\rangle = (|00\rangle + |11\rangle)$$
$$|1\rangle \rightarrow |1_L\rangle = (|01\rangle + |10\rangle)$$

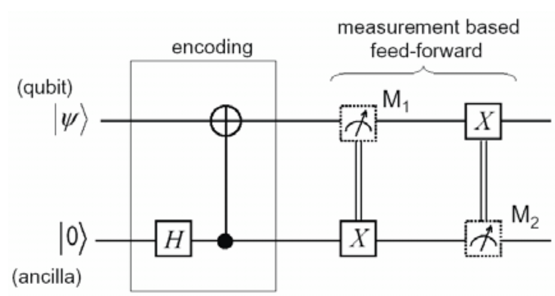

Fig. 6. Parity encoding used to correct for arbitrary z-measurement errors.

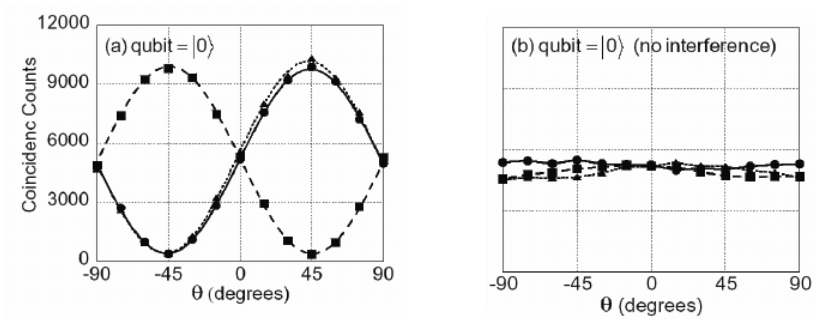

Fig. 7. Experimental results from the first demonstration of quantum error correction using photonic qubits.

In order for any optical approach to quantum computing to be practical, it will be necessary to have an efficient source of single photons on demand. As part of this grant, we developed the single-photon source shown in Fig. 8. Here parametric down-conversion is used to generate a pair of photons. The detection of one member of the pair indicates that the other photon is present with nearly 100% probability. A high-speed switch is then used to store the remaining photon in an optical storage loop until it is needed, at which time it can be switched back out of the loop.

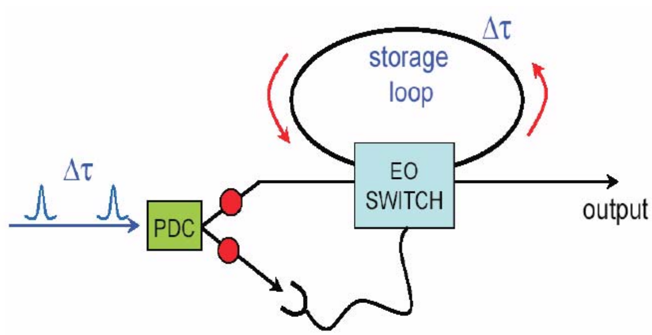

Fig. 8. Single-photon source based on parametric down-conversion and storage of a heralded photon in an optical storage loop.

We have also demonstrated a single-photon memory device based on a similar storage technique. Both of these applictions are limited, however, by the performance of the optical switch. Commercially-available switches are not designed for single-photon use or low loss. This prompted us to begin the development of a more efficient switch

for use in single-photon applications. Some of the preliminary results from this switch are illustrated in Fig. 9.

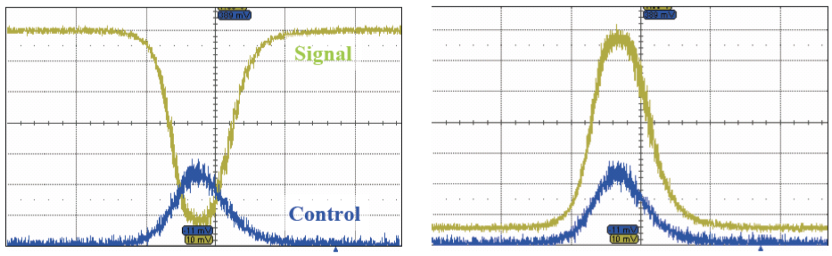

Fig. 9. Preliminary results from an all-optical switch designed for use with single photons.

Although all of the above results are very promising, the remaining difficulty with a linear optics approach to quantum computing is the fact that the logic operations are probabilistic. There are several ways to overcome this difficulty, including the use of cluster states. We are investigating a different solution based on the quantum Zeno effect, in which the occurrence of a random event can be suppressed by frequent observations to determine whether or not it has occurred, as illustrated in Fig. 10.

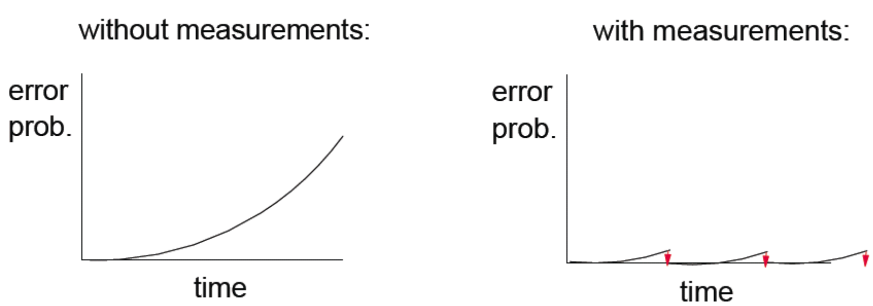

Fig. 10. Suppression of a random error by using the Zeno effect.

All of the failure events in our CNOT gate of Fig. 2 are due to the emission of two photons into the same output path. This can be suppressed using the quantum Zeno effect if two-photon absorbing atoms are present in all of the output paths. Roughly speaking, the atoms continuously "watch" for the presence of two photons, which is sufficient to prevent two photons from ever emerging into the same path. We are currently in the process of developing Zeno gates of this kind by utilizing small resonant cavities to enhance the rate of two-photon absorption compared to the single-photon absorption rate, as illustrated in Fig. 11.

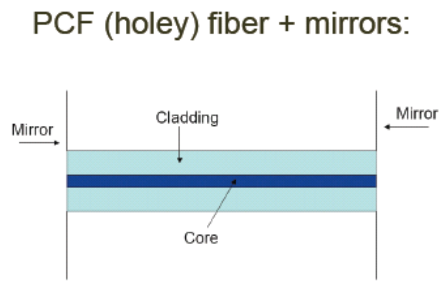

Fig. 11. Small mode volume cavity fabricated from a hollow-core fiber with mirrors on the ends.

In summary, this work has demonstrated many important aspects of a linear optics approach to quantum computing. Combined with the quantum Zeno effect, this approach has many potential advantages for the construction of a full-scale quantum computer.

Publications

Papers published in peer-reviewed journals

"Perturbation Theory for Quantum-Mechanical Observables", J. D. Franson and M. M. Donegan, Physical Review A **65**, 052107-1 to 052107-8 (2002).

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"Experimental Demonstration of Quantum Logic Operations Using Linear Optical Elements", J.D. Franson, B.C. Jacobs, and T.B. Pittman, Proceedings of the IV Adriatico Research Conference on Quantum Interferometry, Trieste, Italy, 11-15 March, 2002 (Fortschr. Phys. **51**, 369-378, 2003). (Invited)

"Dispersion cancellation and non-classical noise reduction for large photon-number states", J. D. Franson and M. J. Fitch, Proceedings of the Quantum Electronics and Laser Science Conference, Long Beach, CA, 19-24 May, 2002 (Optical Society of America, Washington).

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"Experimental Work Towards Linear Optics Quantum Computing: Three-Photon

Interference Experiments", T.B. Pittman and J.D. Franson, to appear in the Proceedings of the 8th International Conference on Squeezed States and Uncertainty Relations, Puebla, Mexico, 9-13 June, 2003. (Invited).

"Periodic Single-Photon Source and Quantum Memory", T.B. Pittman, M.J. Fitch, B.C. Jacobs, and J.D. Franson, to appear in the Proceedings of the SPIE Annual Meeting, San Diego, CA, 3-8 August, 2003.

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"Simple Circuit of Linear Optics Logic Gates", T.B. Pittman, B.C. Jacobs, and J.D. Franson, to appear in the proceedings of the SPIE conference, Denver, CO, August 5, 2004.

<u>Papers presented at meetings but not published:</u>

"High Resolution Quantum Optics Applied to Metrology and Clocks", M. J. Fitch and J. D. Franson, 32nd Winter Colloquium on the Physics of Quantum Electronics, Snow Bird, UT, 6-19 January, 2002. (Invited)

"Demonstration of Non-deterministic Quantum Logic Operations using Linear Optical Elements", T. B. Pittman, B. C. Jacobs, and J. D. Franson, 32nd Winter Colloquium on the Physics of Quantum Electronics, Snow Bird, UT, 6-19 January, 2002. (Invited)

"Experimental Demonstration of Quantum Logic Operations using Linear Optical Elements", J. D. Franson, B. C. Jacobs, and T. B. Pittman, 4th Adriatico Research Conference on Quantum Interferometry, Trieste, Italy, 11-15 March 2002. (Invited)

"Demonstration of Non-Deterministic Quantum Logic Operations using Linear Optical Elements", B. C. Jacobs, T. B. Pittman, and J. D. Franson, Meeting of the Division of Atomic, Molecular, and Optical Physics of the American Physical Society, Williamsburg, VA, 28 May - June 1, 2002.

"Dispersion Cancellation and Nonclassical Noise Reduction for Large Photon-Number States", Quantum Electronics and Laser Science Conference, Long Beach, CA, 19-24 May, 2002.

"Demonstration of Non-deterministic Quantum Logic Operations Using Linear Optical Elements", T. B. Pittman, B. C. Jacobs, and J. D. Franson, Quantum Electronics and Laser Science Conference, Long Beach, CA, 19-24 May, 2002.

“Demonstration of Probabilistic Quantum Logic Operations Using Linear Optics”, J. D. Franson, B. C. Jacobs, and T. B. Pittman, 6th International Conference on Quantum Communication, Measurement, and Computing, Cambridge, MA, 22-26 July, 2002.

“Quantum Logic Operations Using Linear Optical Elements”, J. D. Franson, Nonlinear Optics Conference, Maui, Hawaii, 29 Jul.-2 Aug., 2002. (Invited)

“Quantum Computing Using Linear Optics”, J. D. Franson, B. C. Jacobs, and T. B. Pittman, Feynman Festival Conference, College Park, MD, 23 -28 Aug., 2002. (Invited)

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“Progress in Linear Optics Quantum Computing”, J.D. Franson, M.M. Donegan, M.J. Fitch, B.C. Jacobs, and T.B. Pittman, 33rd Winter Colloquium on the Physics of Quantum Electronics, Snowbird, UT, 5-9 January, 2003. (Invited).

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“Need for High Efficiency Photon-Number Resolving Detectors in Linear Optics Quantum Computing”, T.B. Pittman, M.M. Donegan, M.J. Fitch, B.C. Jacobs, and J.D. Franson, NIST-ARDA Workshop on single-photon detectors, Gaithersburg, MD, March 31, 2003.

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“Discrepancies in the covariant formulation of quantum optics and quantum electrodynamics due to entanglement”, J.D. Franson, submitted to Physical Review Letters.

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Scientific personnel

J.D. Franson – Principal investigator

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S. Hendrickson – graduate student

Report of Inventions

The following patents were awarded by the U.S. Patent Office:

“Optical Method for Quantum Computing”, J.D. Franson, U.S. patent #6,678,450, 13 January, 2004.

“Techniques for Performing Logic Operations using Quantum States of Single Photons”, T.B. Pittman, J.D. Franson, and B.C. Jacobs, U.S. patent #6,741,374, 25 May, 2004.

The following patent applications were submitted:

"Techniques for Quantum Processing with Photons and the Zeno Effect"

"Techniques for Storing a Polarization State of a Single Photon for Retrieving on Demand during Quantum Computing"

"Techniques for High Fidelity Quantum Computing"

Bibliography – see publications

Appendices - none